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ABSTRACT

This report examines basic research needs in forestry and renewable natural resources and determines benefits to be gained from greater investments in basic research. It was prepared by a group of 17 research scientists, each an accomplished investigator in one or more fields. Each contributor reflected on research needs within his own discipline and on integrating knowledge in his specialty with knowledge in other scientific and social areas. The result is a series of recommendations presented in two parts: a list of challenges in basic research for the 20th century (section VII) and a description of the climate and instructional arrangements for basic research (section VIII), the climate required to meet the challenges outlined in section VII. As background for these recommendations, the following areas are discussed in separate sections: (1) basic research and applied research--their interplay and social value; (2) importance of forests and forest products; (3) scientific foundations of forestry and renewable natural resource management; (4) relationships with agriculture and other sciences; (5) distinctive features of forests and related renewable natural resources; and (6) some creative ideas from earlier basic research. (Author/JN)

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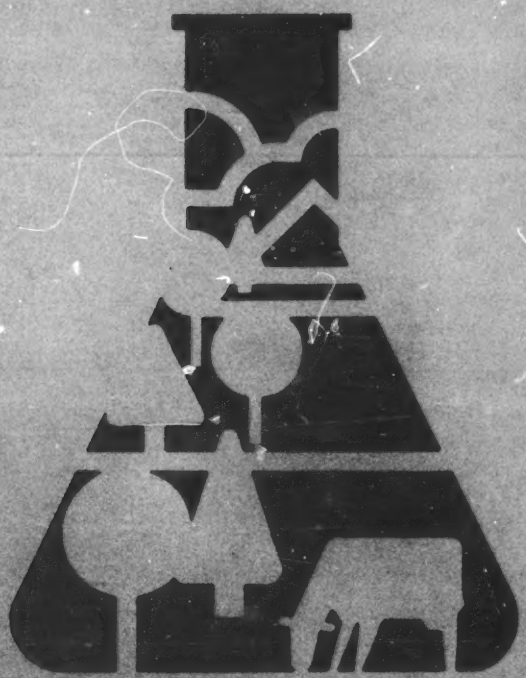

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National Task Force on Basic Research
in Forestry and Renewable Natural Resources

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TABLE OF CONTENTS

Page

MEMBERS OF THE NATIONAL TASK FORCE iv

PREFACE vi

EXECUTIVE SUMMARY vii

INTRODUCTION 1

I. Basic Research and Applied Research–Their Interplay and Social Value 3

Some Essential Definitions 3

II. Importance of Forests and Forest Products for Society 5

III. Scientific Foundations for Forestry and Renewable Natural Resource Management 7

IV. Relationships with Agriculture and Other Sciences 13

V. Distinctive Features of Forests and Related Renewable Natural Resources 14

VI. Some Creative Ideas from Basic Research 15

- Radiotelemetry, Anaesthesiology, and Wildlife Behavior 15
- Parasitic Fungi and Plant Roots 15
- Theory and Methods of Statistical Sampling 16
- Hydrologic Response of a Forested Watershed 17
- Nucleopolyhedrosis Viruses 17
- Nutrient Cycling and Its Relationship to Forest Management, Stream Quality, and Ecosystem Theory 17
- Fire Behavior Models 20
- Fiber Saturation Point and its Significance to Wood Utilization 20
- Chipping Headrig 21
- Selection of Materials for Construction of Laminated Beams With Specific Strength Properties 22

VII. Challenges in Basic Research for the Remainder of the Twentieth Century 23

A. Basic Biology 23
Genetic limits to growth 23
Physiological limits to growth 23
Competitional limits to growth 24

B. Ecological Processes 24
Nutrient, energy, and water transfer processes within forests 24
Interactions with the earth's chemical climate 25
Ecological impacts of wildfires and controlled burning 25

C. Engineering and Material Sciences 26
Reconstituted wood products 26
Forest engineering 26
Wood for fuel and chemical conversion 26

D. Economic and Consumer Benefits 26
Consumer preferences 28
Supply and demand relationships 28
Policy and institutional considerations 28
Damage potential of renewable resources 28

E. Managerial Sciences 29
Sampling and inventory designs 29
Optimization of management alternatives 30
Validation of predictive models 30

VIII. Climate and Institutional Arrangements 31

Choosing the Right Scientists 32
Institutional Arrangements for Basic Research 33
Financial Arrangements for Basic Research 33

EPILOGUE 35

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PREFACE

This report on basic research needs in the forest sciences was prepared at the request of two organizations with a longstanding commitment to the discovery of new knowledge in the sciences underlying forestry and related renewable natural resources: the Association of State College and University Forestry Research Organizations (ASCUFRO) and the United States Department of Agriculture Forest Service (USDA-FS). Both organizations recognize that the scientific foundations for future applied research and development have failed to keep pace with the demand for forest resources. As a result, forest productivity and the productivity of other renewable natural resources confront the possibility of stasis, or even decline, as demand becomes ever greater and more urgent. In short, forestry is "living on borrowed time."

In the fall of 1979, responding to this unsettling possibility, seventeen scientists representing the spectrum of United States forestry research, gathered at Milford, Pennsylvania, at Grey Towers, the family homestead of Gifford Pinchot. For three long and exciting days, these scientists, expert in 27 different disciplines, pondered and debated the needs for new scientific knowledge–knowledge to be gained in the years immediately ahead, knowledge to ensure that future research can provide to management the enlightened guidelines needed during the last years of this century, and beyond.

The result is this report–written and rewritten many times in the months that followed. It is a confident vision of the future of scientific forestry in the United States.

We hope this vision will capture the imaginations of all of those–in the U.S. Congress, in state legislatures, in forest industries, and in scientific institutions–who support the research and discover the knowledge on which tomorrow's management decisions will be founded.

Stanley L. Krugman, Ellis B. Cowling
Co-Chairmen of the Task Group

EXECUTIVE SUMMARY

This report was prepared by a National Task Force on Basic Research. The members, 17 scientists from all sections of the country, collectively represented expertise in 27 of the 48 areas of science and engineering that constitute the scientific foundations of forestry and renewable natural resources management. The following summarizes their views on the needs for basic research in forestry and related renewable natural resources, and includes their recommendations for basic research emphasis and direction.

Basic research in forestry and renewable natural resources is one of the most important sources of ideas for improving the quality of life in the United States. Our forests, for example, can provide a self-renewing energy source, give us the basis for a whole new chemical industry, supply us with better and cheaper building materials. But basic research must supply the ideas–to extend forest productivity, to increase wood utilization efficiency, to ensure water quality, to maintain wildlife and fish populations, to provide recreation opportunities.

Forestry is truly living not only on "borrowed time," but on borrowed resources. We are spending the principal at a faster pace than the interest is accruing. The scientific foundations for future applied research and management decisions are not being adequately replenished. Should this situation continue, we will inevitably confront decreased forest productivity, decreased wood utilization efficiency, deteriorating timber, water, and wildlife conditions, and drastically limited opportunities for recreation opportunities and aesthetic experiences. All these translate directly into a deteriorated quality of life.

This bleak prospect can be averted, by a larger investment in future productivity, a productivity created by a deeper understanding of forestry and related renewable natural resources. We must learn more about:

- how forests grow;
- how forests affect air and surface water quality;
- how forests and range plants can be protected against disease, fire, insects, overgrazing, and human carelessness;
- how wildlife and fish populations respond to changes in habitat and environmental quality;
- how the energy, fibers, and chemical substances accumulated in trees can be used with greatest material and energy efficiency;
- how the satisfactions of individuals and families are influenced by the timber products, forests, wildlife, and surface waters in their surroundings;
- how forest products contribute to the economic well-being of landowners, craftsmen, investors, and even to the international balance of payments for the United States.

To gain the increased and necessary knowledge in these areas, the National Task Force recommends the following:

I. Federal, state, private, and industrial investments in basic research in forestry and related renewable natural resources should be increased substantially during the remaining years of this century.

II. Emphasis should be placed on five primary areas of scientific inquiry:

1. Basic Biology–Much greater understanding is needed of the genetic, physiological, and competitory factors limiting the productivity of forest and range plants, wildlife, and fish. Special efforts should be made to adapt modern genetic engineering, protoplast fusion, and recombinant-DNA research to forest and range plants to accelerate the rate of genetic improvement of forest trees and range plants.

2. Ecological Processes–Basic research is particularly needed on the nutrient-, energy-, and water-transfer processes in

forest ecosystems; on the interactions between forests and the earth's chemical climate, and on the ecological roles of fire, insects and diseases in forests.

3. Engineering and Materials Sciences—Pioneering research is needed on the molecular structure and physics of wood and wood components. This research should emphasize the unique features of wood as an industrial raw material for reconstituted fiber products and for chemical, microbial, and enzymatic conversion processes. New concepts are also needed in the engineering design of forest regeneration and harvesting systems.

4. Economic and Consumer Benefits–New methods are needed to quantify intangible values, to analyze supply and demand relationships for forest products and for water, wildlife, recreation, and amenity values; to determine the potential damage to natural resources of fire, insects, and diseases; and to analyze policy and institutional constraints in natural resource management systems.

5. Managerial Sciences–Basic research is needed in the theory and design of complex resource management systems. Emphasis should be placed on concepts and techniques for sampling and inventory designs, on optimizing and allocating multiple-use outputs, and on validating computer models to be used in evaluating alternatives for managing forests and other natural resources.

III. The intellectual climate and institutional arrangements for basic research will need to be improved in many federal, state, university, and industrial research organizations. Special attention should be given to the factors influencing the creativity of basic research scientists.

1. Special care should be exercised in the selection, evaluation, encouragement, and rewarding of basic research scientists. Not every researcher is prepared by temperament or experience to pursue audacious scientific ideas. Those who are productive should be retained; those who are not should be released.

2. "Freedom to inquire into the nature of things" and protection from bureaucratic impediments are major determinants of motivation and success in basic research. The sole purpose of the business office and the rules and regulations in a basic research institution should be to support the research leaders and scientists on whose productivity and contribution the value of the institution rests.

3. Specific "centers of emphasis in basic research" should be established in carefully selected universities and in federal and state research institutions with distinguished records of achievement in basic research. Decisions about the location and continuation of such centers should be based solely on the creativity, quality, and quantity of new knowledge gained from the research.

4. A carefully controlled mixture of stable and flexible funding should be provided in each area of scientific inquiry. Such support should be maintained long enough to ensure maximum productivity and creativity in the chosen research.

A long-term investment in increased basic research will pay handsome dividends to society and to the industrial enterprises on which our economy depends.

INTRODUCTION

The United States is rich in forests and related renewable natural resources. These resources must be managed and used wisely if Americans are to enjoy the full complement of forest-provided values–jobs, wood, wildlife, water, range, and energy–and a varied array of aesthetic and recreation values. Wise management, in turn, requires scientifically sound knowledge and an understanding sensitively attuned to human needs–be they material, aesthetic, or social.

Just as the forest resources of the United States are many, diverse, and constantly changing, so, too, are the demands upon them. In consequence, learning how forests grow and how people use (and sometimes abuse) forest-related resources presents a difficult but necessary challenge to scientists and scholars in many fields. The challenge may be hard, but the stakes are commensurately high.

To meet the challenge and to construct from the knowledge gained guidelines for wise natural resources management require integrated research in the biological, physical, and social sciences. Unfortunately, in recent years, changes have occurred in the nature, goals, and institutional arrangements for research in forestry and related renewable natural resources. Current research tends to be either applied research with short-term potential for social benefit or research narrowly focused within a given scientific discipline–often without appropriate regard for its integration with knowledge in other scientific fields or for the managerial arts by which natural resources are conserved and used. Longer-term management problems and serious basic research needs have been neglected.

The pursuit of narrow, short-term goals threatens to sacrifice the construction of scientific foundations for future applied research and management decisions. Should that pursuit continue, unmitigated by broader, integrated and multidisciplinary research founded on long-term considerations, the inevitable result will be less productive forests, less efficient management and use, and deteriorating timber, water, wildlife, recreational experiences, and aesthetic values.

This bleak prospect can be averted, by a larger investment in future productivity, productivity founded upon a deeper understanding of forestry and related renewable natural resources. We must learn more about:

- how forests grow;
- how forests affect air and surface water quality;
- how forests and range plants can be protected against disease, fire, insects, overgrazing, and human carelessness;
- how wildlife populations respond to changes in habitat quality;
- how the energy, fibers, and chemical substances accumulated in trees can be used with greatest material and energy efficiency;
- how individual human beings and families are influenced by the timber products, forests, wildlife, and surface waters in their surroundings;
- how timber and fiber products contribute to the financial well-being of landowners, craftsmen, investors, and even to the international balance of payments for the United States.

This report examines basic research needs and determines benefits to be gained from greater investments in basic research. It has been prepared by a select group of 17 research scientists, each an accomplished investigator in one or more fields. Each contributor reflected upon research needs within his own discipline and upon integrating knowledge in his specialty with knowledge in other scientific and social areas.

The result is a series of recommendations presented in two parts: (1) a list of Challenges in Basic Research for the Remainder of the 20th Century (Section VII); and (2) a description of the Climate and Institutional Arrangements for Basic Research (Section VIII)–the climate required to meet the Challenges outlined in Section VII.

As background for these recommendations we will discuss the following:

I. Basic Research and Applied Research–Their Interplay and Social Value;

II. Importance of Forests and Forest Products;

III. Scientific Foundations of Forestry and Renewable Natural Resource Management;

IV. The Relationships with Agriculture and Other Sciences;

V. Distinctive Features of Forests and Related Renewable Natural Resources;

VI. Some Creative Ideas from Earlier Basic Research.

I. BASIC RESEARCH AND APPLIED RESEARCH– THEIR INTERPLAY AND SOCIAL VALUE

"Our research must be good, but it must be good for something."

Norman Borlaug

In recent years, much has been written about the distinction between basic and applied research. One of the most eloquent of recent analyses was published by Isaac Asimov in the *Saturday Review* for June 1979. In this article, "Pure and Impure–The Interplay of Science and Technology," Asimov reviews the history of science (the pursuit of knowledge) and the history of technology (the art of making things useful) and the necessity for interplay between the two. Writes Asimov:

> Scientists tend to divide science into two parts; one deals with the difficult, the abstruse, the elegant, the fundamental–in other words, "pure science," a truly liberal art. The other type of science is any branch that goes slumming and becomes associated with such mechanical (useful) arts as medicine, agriculture, and industry–clearly a form of impure science . . . . We can therefore speak of "science" and "technology" and we know very well which is the loftier . . . of the two. Yet the division is man-made and arbitrary and has no meaning in reality. The advance of knowledge of the physical universe rests on science *and* technology, neither can flourish without the other . . . .
>
> It was only when scientists began to observe the real world and to manipulate it that "experimental science" arose. This was in the 16th Century, and the most able practitioner was the Italian scientist, Galileo Galilei, who began work toward the end of that century. Thus, began the Scientific Revolution.
>
> In the 18th Century, when enough scientists recognized their responsibility toward the mechanical (useful) arts, we had the Industrial Revolution; it reshaped human life.
>
> Such is the psychological set of our minds toward separation of science into pure and impure, basic and applied, useless and useful, intellectual and industrial, that even today it is difficult for people to grasp the frequent and necessary interplay between them. . . .
>
> The fact is that science and technology are one . . . there is only one scientific endeavor on earth–the pursuit of knowledge and understanding–and all the divisions into disciplines and levels of purity are but man-made ways of obscuring *that* fundamental truth.

If we accept Asimov's analysis and assert that basic and applied research are one, can we at the same time claim that basic research in the forest sciences is being neglected? Indeed we can, for support of the practical to the exclusion of the theoretical leads to a lack of "interplay," as Asimov describes it, and, thus, to neglect of fundamental discoveries on which future useful discoveries will depend.

In a democratic society, the challenge confronting supporters and managers of scientific enterprises is ensuring that an adequate, productive balance is maintained between research that is "pure and impure, basic and applied, intellectual and industrial." This "principle of balance and interplay" applies to every realm of science, not just to forestry and related renewable natural resources. Discoveries about how forests grow and how people enjoy them will help us better understand how to manage forests for all the varied purposes for which people wish to use them.

Some Essential Definitions

The following definitions are offered as reference points:

Science is the discovery of new knowledge and understanding through research.

Research is an orderly process of inquiry into the nature of things and the ways they function. Research involves hypotheses, measurements, test-

ing, and the development of conclusions based on inductive and deductive reason. Research in the forest sciences involves inquiry into the nature, composition, and development of forests and all of their derived products and values for society.

Basic research in natural resources is inquiry aimed at attaining a fuller knowledge and understanding of the fundamental structures, processes, and relationships within forests and related renewable natural resources, their derived products, and the enjoyment of these resources by human beings. Attainment of this fuller understanding requires inquiry into all the physical, chemical, biological, and human factors affecting the productivity, stability, and enjoyment of forests and forest products.

Applied research is inquiry aimed at discovering useful principles and guidelines for management, utilization, conservation, and enjoyment of forests and all of their derived products and values (Figure 1). Applied research is the foundation for the development of useful technology. As Isaac Asimov said, "The advance of knowledge . . . rests on science *and* technology, neither can flourish without the other."

Forests and related renewable natural resources or simply *natural resources* are expressions used herein to refer to all the biological and physical resources present in or on the nonculti-vated and forest-cultivated lands and surface waters of the United States. These resources include: herbaceous and woody vegetation; soils; wildlife of all sorts (including birds, fish, mammals, reptiles, and insects); microorganisms both beneficial and detrimental; water in all of its atmospheric, surface, and underground forms, including lakes, streams, rivers, estuaries, and aquifers; the geological substrata and minerals below the land surface; and the atmosphere. Thus, natural resources include all the living organisms, all soils, water and air resources, and all the people who derive their livelihood from the land. Forests and related renewable natural resources include timberlands, forest-related rangelands, grasslands, brushlands, wetlands and swamps, alpine lands and tundra, deserts, wildlife habitat, and watersheds. These resources include many different categories of ownership: national forests, parks, and grasslands; federal, state, and private wildlife areas; state, county, municipal, and private forests; urban and suburban forests and parks; private nonindustrial timber and rangelands; and industrial forests and rangelands.

Forestry consists of the science and practical arts applied to manage and use forests and related renewable natural resources. Thus, forestry activities include: timber management; wildlife management; range management; watershed management; disease, fire, and insect protection; harvesting, transporting, manufacturing, marketing, preserving, and protecting forest products; the maintenance of scenic vistas and aesthetic values; the maintenance of water and air quality; and the society's well-being as it is influenced by forests and other natural resources and their products.

Figure 1. Winter-time access to forests in mountainous regions is essential for both forest operations and recreational facilities such as ski resorts. Basic research on the micrometeorology of windblown snow will provide the theoretical foundation for improved design of practical and efficient snow fences.

II. IMPORTANCE OF FORESTS AND FOREST PRODUCTS FOR SOCIETY

"Scientific methods are not scientific unless they are practical, and they are not practical unless they are scientific."

H. H. Whetzel

One-third of the land area of the United States (700 million acres) is forested. Ecologically, this area varies from mesquite brushland, rangelands, and swamps and bogs (where the trees are barely identifiable as such) to the magnificent coniferous forests of the Pacific Coast and the colorful hardwood stands of New England. A measure of the diversity of forest ecosystems can be seen in the changes occurring with elevation in the major mountain ranges. In a day's climb, one can pass from subtropical desert to alpine meadow, from bottomland swamp to heath-like tundra. The mix of plant and animal species one observes may be comparable to that of a latitudinal spectrum of 1000 miles or more.

The forested areas of the United States are classified according to various botanical, edaphic, climatic, and socioeconomic criteria. However, most descriptions, being essentially static, do not adequately communicate the total diversity, complexity, and changing nature of forests as ecosystems. Dynamic forces are at work in every forest, and the continuing interplay of biosynthetic and destructive forces–the cumulative net effects of these competing forces–determines the character and productivity of a forest.

Forests provide renewable resources for many of our needs:

- lumber, plywood, and other forest products for homes;
- wooden furniture, implements, and a myriad of other everyday items;
- paper products in prodigious amounts–more than 600 pounds annually for every man, woman, and child in the United States;
- cellulose and other wood-based chemicals, including such special products as turpentine and maple sugar.

Forests and rangelands also shelter and feed birds, fish, and many game animals. They provide protective cover and regulate streamflow in watersheds. They help replenish atmospheric oxygen and serve as metabolic sinks for removing or modifying atmospheric pollutants. Moreover, forests provide places of beauty and recreation where people can retreat from the tensions and frustrations of everyday life and find rest and inspiration (Figure 2).

We must learn to exercise a more responsible stewardship over these resources, ensuring that society's demands do not exceed the sustainable productive capacity of our natural resources.

In practice, certain social, political, and economic constraints significantly influence investments in forestry research:

1. Forests provide only small annual increments of value per unit of land area–typically $10 to $35 per acre per year.
2. The total values accumulated over the full time span of a forest crop can be quite large–often $1000 to $4000 per acre, and in some cases as much as $10,000 or more.
3. Where timber values are paramount, many years or even decades may elapse between the time a given management treatment is applied and the recovery of that investment through harvest.
4. Forests are owned and managed by many different persons and organizations with a great diversity of management goals. Private individuals and corporations own about 73 percent of the commercially productive forest land of the United States; the remainder is in federal, state, and other public holdings.

About 20 percent of the commercial forest area is in holdings of 50,000 or more acres and is managed by about 300 large corporations and government agencies. All but 30 percent is in small woodlots of 100 or fewer acres owned by nearly 4 million private individuals.

5. Most intangible values of forests and related renewable resources are difficult to quantify. Estimated prices for harvested timber in current and future rotations can be used to calculate benefits and costs for research affecting timber production. More difficult, however, is developing rational benefit-cost estimates for the less tangible values associated with water yields and quality, wildlife populations, and the aesthetic and amenity values of forest and other natural resources.

Figure 2. Forests provide many renewable resources for our society. They also provide a unique environment for inspiration and a refuge from the everyday tensions of life. They provide places of beauty and recreation. Here campers enjoy the Mark Twain National Forest, Missouri.

III. SCIENTIFIC FOUNDATIONS FOR FORESTRY AND RENEWABLE NATURAL RESOURCE MANAGEMENT

"The difference between those who advance the frontiers and those who merely exist in science is the ability to choose the right problem."

Eric Ellwood

As Table 1 shows, forestry and renewable natural resources management embraces many diverse areas of science, engineering, and the managerial arts. A wide array of biological disciplines is essential. Important, too, are the various physical sciences from meteorology, photogrammetry, and mensuration to soil science, geology, and hydrology. Various types of engineering are involved in such forest operations as harvesting, land drainage, watershed management, forest regeneration, and forest road construction and maintenance.

Essential, too, are the practical arts of management. Business management, forest management, wildlife management, range management, watershed management, and fire management are familiar specialties to public and private owners of forest and range lands.

Table 1. Examples of scientific disciplines important to forestry and renewable natural resource management.

Biological sciences	Physical and mathematical sciences	Engineering and managerial sciences	Social sciences
Aquatic Biology	Chemistry	Biological Engineering	Economics
Biochemistry	Climatology	Chemical Engineering	Aesthetics
Botany	Computer Science	Civil Engineering	Environmental Sciences
Ecology	Fiber and Polymer Science	Mechanical Engineering	Law
Entomology		Operations Research	
Genetics	Geography	Business Management	Psychology
Microbiology	Geology	Fire Management	Recreation
Mycology	Hydrology	Forest Management	Social Ethics
	Limnology		Sociology
Plant Physiology		Recreation Management	
Plant Pathology	Mensuration	Range Management	
Silvics	Meteorology	Silviculture	
Taxonomy	Photogrammetry	Water Resources Management	
	Physics		
Wildlife Biology			
Zoology	Pulp and Paper Science and Technology	Wildlife Management	
	Soil Science		
	Timber Mechanics		
	Statistics		
	Wood Chemistry		
	Wood Technology		

Table 2. Examples of scientific disciplines important to selected aspects of renewable resource management.

Biological sciences	Physical and mathematical sciences	Engineering and managerial sciences	Social sciences
Wildlife Management			
Aquatic Biology	Climatology	Biological Engineering	Economics
Botany	Geography	Range Management	Law
Ecology	Hydrology	Wildlife Management	Recreation
Genetics	Limnology		Social Ethics
Silviculture	Mensuration		Sociology
Taxonomy	Meteorology		
Wildlife Biology	Statistics		
Zoology			
Watershed Management			
Aquatic Biology	Chemistry	Biological Engineering	Aesthetics
Ecology	Geology	Civil Engineering	Economics
	Hydrology	Operations Research	Law
	Physics	Water Resources Management	Recreation
	Soil Science		
Recreation Management			
Botany	Computer Science	Business Management	Aesthetics
Ecology	Hydrology	Civil Engineering	Economics
Silviculture	Meteorology	Operations Research	Law
	Photogrammetry	Recreation Management	Psychology
	Statistics		Recreation
			Social Ethics
			Sociology
Harvesting of Forest Products			
Silviculture	Mensuration	Business Management	Aesthetics
	Photogrammetry	Civil Engineering	Economics
	Soil Science	Forest Management	Law
		Mechanical Engineering	
		Operations Research	
Development of Wood for Energy			
Botany	Chemistry	Business Management	Aesthetics
Ecology	Computer Science	Chemical Engineering	Environmental Science
Genetics	Mensuration	Civil Engineering	Economics
Microbiology	Photogrammetry	Forest Management	Law
Plant Pathology	Pulp and Paper Science and Technology	Operations Research	
Plant Physiology	Soil Science	Mechanical Engineering	
Silviculture	Wood Technology		

Economics leads the list of relevant social sciences. Very few things can be done without some consideration of cost and benefits. But sociology, psychology, recreation, social ethics, and law are likewise essential to rational management and use of forests and other natural resources.

Even within a fairly restricted aspect of natural resource management–such as wildlife management or harvesting of timber products–a diverse array of scientific disciplines is employed. In Table 2, five specific aspects of natural resource management or forestry operations have been selected to illustrate this principle. In every case, knowledge in a broad array of biological, physical, mathematical, engineering, managerial, and social sciences is needed if wise management plans are to be formulated.

A short comment may be useful about each aspect of forestry included in Table 2. *Wildlife management* planning, for example, requires a knowledge of many aspects of wildlife biology: reproductive behavior, habitat and food requirements, ranging habits, population dynamics, predator-prey relationships, disease incidence and toxicology, and principles of territoriality, competition, and carrying capacity. Effective planning also requires a knowledge of weather and climatic influences on wildlife and an understanding of human desires for observational and consumptive hunting experiences (Figure 3).

Watershed management is similarly complicated because so many different factors influence the availability and quality of surface and ground waters. Among them are: seasonal variation in amount and form of precipitation, the changing chemistry of rain and snow, geology and soils of the drainage basin, type of vegetational cover and its ability to regulate streamflow and water yield, seasonal changes in evapotranspiration rate, land-use patterns in the drainage area, size of catchments, recharge potential of the soils and natural aquifers within the drainage basin, seasonal water demand rates, consumers' water quality standards; fishing, boating, camping, and other recreational uses of the watershed and its reservoirs; cost of water-treatment facilities, and the traditions and legal definitions of water rights (Figure 4).

Recreation management involves more human and social science considerations than either wildlife or watershed management. Factors affecting the recreational use of a given forest area include:

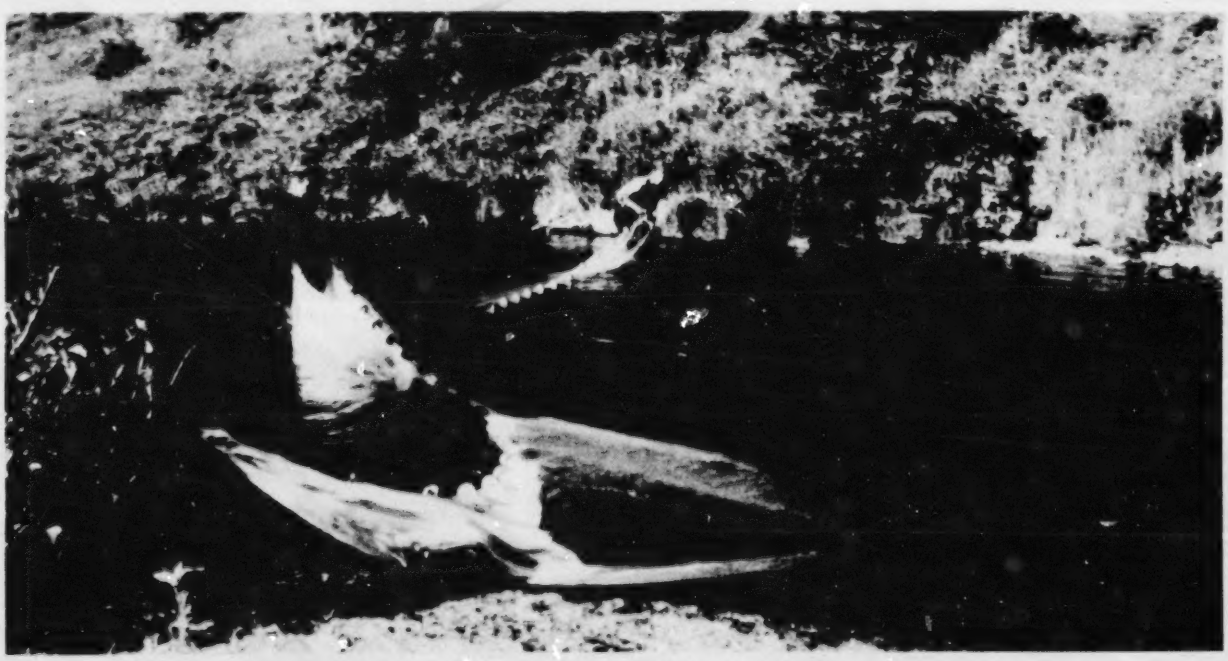


Figure 3. Lakes and streams provide valuable recreational experiences for many fishermen. Basic research is needed to determine how fish populations change with different patterns of land use, fishing pressure, or pollution controls that affect the geographical or seasonal occurrence of acid rain. Seine nets such as this are one tool by which studies can be made of the movement of fish in response to changes in water quality.

Figure 4. The quality and seasonal supply of water for many cities and towns are determined by the nature of the forest cover on watershed areas. Basic research in forest hydrology will provide improved understanding of how the chemistry and seasonality of precipitation interacts with the forest cover to provide a reliable supply of water in municipal reservoirs.

distance from population centers; weather and climatic influences on recreation potential; socio-economic status, age, and recreational preferences of potential users; seasonality of demand for recreation; carrying capacity of the site; type of soils, vegetation, wildlife, water resources on the site; type of ownership—whether private, municipal, county, state, or federal; funds for development, supervision, and maintenance; public attitudes and traditions regarding recreational use of the site, payment of user fees, etc.; problems of vandalism, crime, and other aspects of public safety. (Figure 5).

Harvesting of forest products involves another unique set of scientific fields. Harvest planning begins with a consideration of ownership goals—a matter of public or private opinion and market analysis. Next, the standing timber must be measured by one or another mensurational system. Once the volume of marketable products is estimated, requests for bids and logging contracts must be negotiated—a matter of business management and legal requirements. If access roads must be built, civil engineering skills must be brought into play. Soil science helps determine the bearing and shear strength of soils, proper bridge and drainage design, and the requirements of erosion control. The logging job itself must be planned. If high-lead, balloon, or other cable systems are to be used, other engineering skills must be applied, particularly in steep terrain or on wetland sites. Finally, mechanical engineering skills are applied to determine felling, bunching, cutting, chipping, or whole-tree harvesting systems appropriate to maintaining the productive potential of the site and regenerating the next crop of timber (Figure 6).

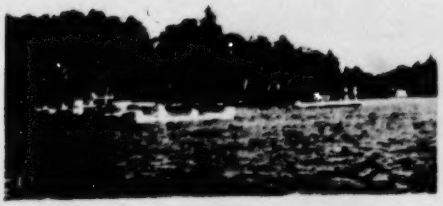
POPULATION CENTER

1. TRAVEL TIME TO THE CAMPING AREA

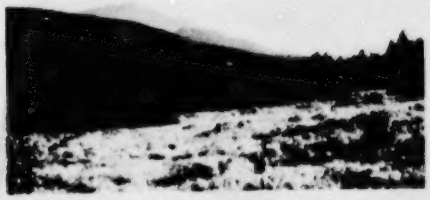
6. CAMPING AREA RECOMMENDED BY FRIENDS

2. NEARNESS TO WATER

5. TOURIST ATTRACTIONS NEARBY



3. SWIMMING AND WATER SPORTS ACCOMMODATONS



4. VARIETY OF LANDSCAPE

Figure 5. The design and maintenance of facilities for outdoor recreation require an understanding of how people make decisions about alternative recreational opportunities. Basic research on the satisfactions people derive from various types of recreational experiences will make it possible to better allocate available resources for construction and maintenance of facilities. This figure shows several factors vacationing families consider in making their choices about recreational opportunities.

Using wood as a source of energy, though an ancient art, requires a wide range of scientific and engineering considerations when practiced today. Environmental, aesthetic, and safety considerations are much more important than in earlier eras of fuelwood use. Environmental considerations include air quality relative to human health—especially in cities and towns—nutrient drain from intensive biomass harvest, erosion of steep terrain, influence of fuelwood cutting on timber quality in forest stands, and abuse of forest soils with four-wheel-drive vehicles. Aesthetic considerations include the appearance of piles of cordwood in home yards, harvesting debris left in the forest, and influences of open fires and wood stoves on patterns of family life.

Safety considerations include the hazards woodcutters incur while felling trees, using power saws, splitting or chipping wood, and transporting wood in trailers and small trucks. Wood burning safety involves installing and operating wood stoves, particularly as regards flammable residues deposited in chimneys.

Various technological and economic issues are also involved in the choice of a wood-burning apparatus—from simple stove to sophisticated wood-gasification equipment—and in methods of transporting and storing wood fuel before and after shipping, splitting, cutting, pelletizing or gasifying the material. Other considerations involve the convenience, cost, and availability of alternative energy sources, issues related to the state or national balance of payments.

Tables 1 and 2 show that basic research needs germane to forestry and related renewable resource management extend very broadly across the spectrum of science and technology. In forestry, knowledge from many fields must be integrated, a need made all the more urgent by the multiple and sometimes conflicting demands placed on forest managers by a constantly changing, increasingly sophisticated society. The same forest area, for example, is often simultaneously managed for the enjoyment of multiple benefits—including water, grazing, recreation, wildlife, pulpwood, sawtimber, and other products. Choices about particular patterns of use of timber products often significantly influence other sectors of the local, national, or international economic system.

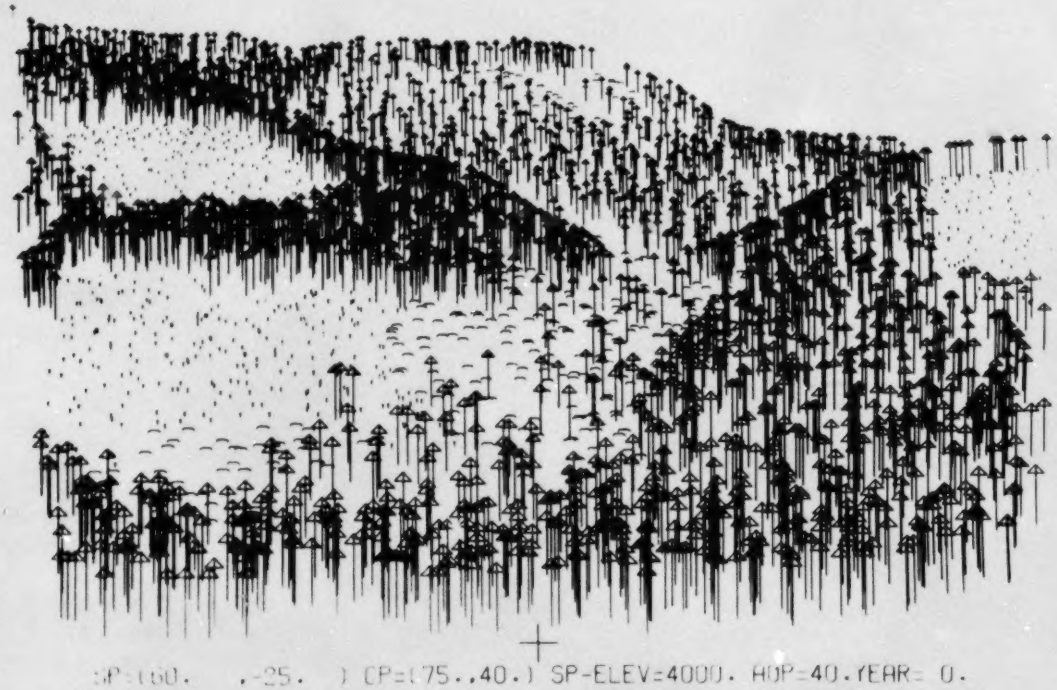


Figure 6. The visual quality of forested landscapes can be influenced greatly by timber harvesting, road construction, and other management practices. Basic research or computer graphics is making it possible for forest managers to "see" and evaluate in advance the visual impact of specific management alternatives.

IV. RELATIONSHIPS WITH AGRICULTURE AND OTHER SCIENCES

"The modern danger is that the specialists may lose touch with one another and the subject may end up as it began; as a mass of facts of greater or less moment, out of which a clear and lucid system is still to be formed."

Sir John Russell

Forestry and agriculture share many of the same scientific roots—botany, zoology, soil science, genetics, mycology, plant physiology and pathology, entomology, microbiology, and statistics. Silviculture is the scientific counterpart of horticulture or agronomy. Certain specialized fields of forestry, such as wildlife biology, forest engineering, and forest economics, have profited from related scientific endeavors in animal husbandry, agricultural engineering, and agricultural economics.

Meeting human needs for food and fiber is the primary mission of agriculture. Providing timber, fiber, and certain chemical products is an important mission of forestry. Thus, forestry is often viewed as an extension of agriculture, and forestry research as an extension of agricultural research. Unfortunately, however, the impression that forestry is an extension of agriculture has sometimes worked to the disadvantage of forestry research. For example, state and federal investments in agricultural research in the southeastern states have typically averaged about $4 to $6 per year for each acre of agricultural land compared to $0.04 to $0.06 per acre per year for forest land. Although economic returns per acre are larger for agricultural crops than for forests, the average differential in income per acre is far less than the 100-fold difference in research investment. As Marion Clawson, economist with Resources for the Future, stated so well: "Forestry is the branch of agriculture with the greatest potential for increase in productivity."

Just as agriculture has profited from investments in medical research, so, too, has forestry profited from investments in agricultural research. Basic research discoveries in such fields as plant physiology, animal nutrition, genetics, biochemistry, plant pathology, entomology, polymer science, and biometeorology have stimulated rapid advances in, respectively, forest nutrition, wildlife biology, tree breeding, wood chemistry, forest pathology, forest entomology, cellulose chemistry, and forest meteorology. The flow of ideas between agriculture and forestry has been predominately from agriculture to forestry, due mainly to the much larger investments in agriculture research. However, some notable examples of discoveries in forestry research have benefited agriculture, as well as other sciences. The most important of these have been in sampling theory, ecology, hydrology, soil microbiology, and the economics of intangible values—fields of science in which necessity, deriving from certain distinctive characteristics for forestry, has indeed been the mother of invention.

But critical differences exist between forestry and agriculture. Forests must be managed over very long periods of time, while many agricultural products are harvested annually. Because of the vast size of forests and their natural state, management necessarily tends to be extensive compared to the highly intensive nature of agricultural management. Forestry generally manages for an array of very different products simultaneously, while in agriculture, relatively few commonly related products are produced in a given area. While agricultural plots are man-made, forests are essentially developed by natural systems. These natural systems are highly complex and can be essentially unique in certain features from one forest area to the next. Agricultural or even traditional biological basic research efforts fail to address these unique features of the forest system.

V. DISTINCTIVE FEATURES OF FORESTS AND RELATED RENEWABLE NATURAL RESOURCES

"Man's mind stretched to embrace a new idea never returns to its original dimension."

Oliver Wendell Holmes

How do forests differ from other natural resources? In what ways do their features affect management requirements and posit unique basic research needs? These questions can be answered by analyzing the nature and human significance of natural ecosystems.

Forests and related renewable natural resources are complex ecosystems resulting from millions of years of evolutionary changes in geology, climate, and genetic diversity. These natural ecosystems, consisting of an immense variety of geologic features and life forms, include many plants and animals of considerable commercial and aesthetic value. Because of these special characteristics and their renewability, natural ecosystems constitute an essential part of our natural, economic, and cultural heritage, adding immeasurably to the abundance and the quality of life. They must be conserved to enrich the lives of present and future generations.

America's natural ecosystems occupy vast reaches of our continental land area—more by far than is occupied by all other uses of land combined. Without human disturbance, forests tend to persist in substantially unaltered form over long periods of time, thus providing stable landscapes and watersheds and critical habitat and food for wild game, birds, fish, and invertebrate animals of many sorts. The natural ecosystems receive, purify, and regulate the flow of clean water and replenish atmospheric oxygen. As they mature, forest ecosystems accumulate large quantities of fiber, chemical, and energy resources that can be harvested periodically. These materials can be used on a sustained yield basis to provide a great variety of commercial products.

The products of natural ecosystems flow from the watersheds and commercial timberlands of our continent into agricultural and industrial sites and human habitations throughout the nation and the world. These ecosystems also provide appealing contrasts to urban and industrial areas-places of beauty and recreation where we can rest, find inspiration, fun, and a refuge from some of the tensions and frustrations of modern life. Indeed, America's social health and economic prosperity are inextricably bound to the health and productivity of the forests and other renewable natural resources.

For many centuries, human behavior and attitudes have been conditioned by experiences associated with forests. As a result, people perceive forests in a great variety of ways—both protective and threatening, both supportive and obstructive. During the colonial period, the clearing of forest land by burning was necessary to provide agricultural land and herbaceous vegetation for grazing livestock. Later, very selective cuttings were made for specific economic and utilitarian purposes such as growing white pine for ship masts. Early forest exploitation has greatly complicated management. Since the Civil War, an expanding domestic and world population, technological innovations, human mobility, and urbanization have brought new and increased demands on forest resources. These forces have caused major shifts in demand for wood, water, wildlife, chemical products, energy, wilderness, and amenities.

New knowledge had to be discovered. New technologies had to be developed. New generations of scientists, engineers, technicians, and managers had to be educated. For decades now, the nation's research and educational establishments have been pressured to create a constantly increasing base of scientific knowledge, technological innovations, and well-qualified manpower. Pressures have been strong and successes have been notable (see Section VI). But the wellspring of fundamental knowledge from which new management systems must be derived is no longer adequate to assure continuing success. If the quality of natural resource management is to continue to improve, the present state of theory and understanding of complex systems must be advanced.

VI. SOME CREATIVE IDEAS FROM BASIC RESEARCH

"Innovative ideas spring almost full blown
from the prepared mind of the inventor.
Patent law calls this a 'flash of genius.'
Flashes of genius come to individuals,
not to committees who frequently don't
even notice the flash."

James Horsfall and Ellis Cowling

Earlier in this report, basic research in the forest sciences was defined as inquiry aimed at reaching a fuller understanding of the fundamental structures, processes, and relationships within forests, their derived products, and the enjoyment of these resources by human beings.

The most compelling justification scientists can offer for increased public and private investments in basic research is to show that past basic research has paid handsome dividends in terms of positive benefits for society. The following are a few typical examples of creative ideas and useful technology that originated from earlier basic research.

Radiotelemetry, Anaesthesiology, and Wildlife Behavior

Until recently, research into the mobility of wildlife has been handicapped by the influence of the observer on the wildlife being studied. Early research by Cochran and others led to the development of a technology and system for tracking animals from distant locations, and thus to a much fuller understanding of animal behavior and habitat. The key to success was the development of very small radios and battery packs that could be attached to wildlife captured with the use of anesthetic drugs. The ultimate of miniaturization and attachment is a radio that will function well for tracking purposes after the animal has ingested it with its food.

Similar systems have been used to track astronauts on the moon, to follow the movements of suspected criminals, to locate rabid dogs, and to further rat control programs in cities. Also, observation of anesthetized wild animals has increased knowledge in medical anesthesiology. A remarkable array of public benefits was generated from creative research in wildlife biology (Figure 7).

Parasitic Fungi and Plant Roots

Pioneering research by forest pathologists has led to discoveries in tree nutrition, the nature of parasitism, revegetation of disturbed lands, and practical applications in agriculture. For many years it has been known that tree roots are often infected by fungi that modify root structure. Curiosity about the nature of these specialized fungi led to the realization that trees in some habitats are absolutely dependent on these beneficial parasites. These unique root structures are called mycorrhizae (myco meaning fungus, rhizo meaning root). In a remarkable example of symbiosis, the root provides carbohydrates for the fungi, while the fungi spread through the soil, absorb essential nutrients, and transport them back to the tree. Not only is there a mutually beneficial exchange of nutrients, but the mycorrhizal fungi also benefit the tree by: (1) protecting feeder roots against virulent soil pathogens; (2) protecting feeder roots against elevated temperatures, moisture stress, and acid drainage from mine spoils on drastically disturbed lands, and (3) increasing the ability of trees to compete with grasses, weeds, and other competing vegetation.

Earlier, it was believed that fertilizing tree seedlings in a forest nursery would inhibit mycorrhizae formation. Very recently, Marx discovered that fumigation of nursery soils coupled with massive inoculation of specific mycorrhizal fungi permitted the development of vigorous seedlings with mycorrhizae sufficient to increase the growth of seedlings on difficult sites. Within

the last few years, the productivity of citrus orchards has also been increased by adding specific mycorrhizal fungi to orchard soils. Basic research in agriculture frequently provides practical benefits to forestry, but, in this case, basic research in forestry led to more productive agriculture.

Theory and Methods of Statistical Sampling

Research in forest mensuration has helped to develop entirely new theories and highly cost-effective methods for sampling in heterogenous populations. Several unusual problems in measuring forest resources make it impossible to use the standard theory and methods of statistical sampling. Necessity spurred the development of new statistical theory and sampling methods for applications not only in forestry, but also in other areas of science and natural resource management.

These contributions have advanced the knowledge of systematic sampling, capture-recapture sampling for animal populations, combined remote-sensed and ground observed sampling, sampling with partial replacement on successive occasions, and unequal probability sampling and ranked-set sampling.

Foresters used systematic strips and line plots even before there was concern with statistical probability sampling. Similarly, the need to estimate numbers of mobile animals in large areas led to developing the Lincoln Index procedure of estimation based on capturing and tagging a number of animals, releasing them and recapturing the population. The proportion of animals recaptured was used to estimate total wildlife numbers. These methods are now widely used in ecological

Figure 7. Management of moose populations requires understanding the amount of land individual moose travel in search of food and vegetational cover. Past basic research on the ranging habits of these animals has been greatly improved by the use of modern methods of radiotelemetry after capturing moose with anesthetic drugs. Future basic research will aid forest managers in maintaining populations of these remarkable creatures in areas where they can be seen and appreciated by visitors to the national parks.

Figure 8. Basic research on the habitat requirements and reproductive behavior of grizzly bear and other endangered wildlife species will help forest managers determine where and under what conditions refuge areas for these species have the best chance for successful development.

studies, as well as for controlling harvesting of fish, wildlife, etc. (Figure 8).

During World War II, the technology of aerial photogrammetry was worked out and applied to military objectives. Immediately afterward, however, the potential importance of this methodology for measuring inaccessible forest resources was realized. Research in forest photogrammetry and remote sensing led not only to significant developments in those sciences and technologies, but also to the development of new sampling designs, theory, and methods involving combinations of data obtained by sampling through remote sensing and data obtained by ground observations.

The need to determine the state of forest resources on a continuing basis led to developing new sampling procedures involving permanent remeasured sampling units. The high cost of maintaining permanent plots led to the idea of sampling with partial replacement on successive occasions. Application of these concepts and methods to forest inventory has greatly reduced costs.

Hydrologic Response of a Forested Watershed

Beginning in the 1980's, several concepts were developed to explain the movement of water from the surface of a watershed to a stream channel. These concepts of "classical hydrology" formed the principal basis for calculating the hydrologic balance and the design of flood-control programs. Recent basic research by forest hydrologists has shown this classical theory to be incorrect, that most of the precipitation enters the soil surface and moves through the soil quickly enough to increase stormflow (floods). In addition, hydrologists found that only portions of the watershed contribute to stormflow rather than the entire watershed, as in classical hydrologic models. Further refinement of these concepts has led to a better understanding of nutrient cycles, of the hydrologic cycle, and of water quality and watershed response associated with forest manipulation (i.e., application of fertilizers, pesticides, wastes, etc.). Agriculture and associated land management activities are now incorporating these concepts into models for irrigation projects, waste disposal systems, etc.

Nucleopolyhedrosis Viruses

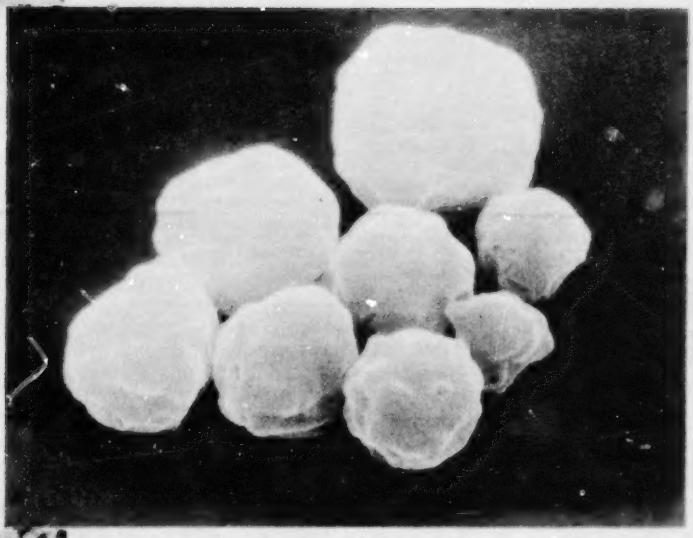
These remarkable viruses--called NPV's for short--were first discovered in the silkworm. But their potential as a biological control agent was first recognized by forest entomologists concerned with the nun moth in Europe and the gypsy moth in the United States. Identification and characterization of the unique structure and properties of the NPV's was made in 1948. Since then, intensive laboratory and field studies of the efficacy, safety, production, control, and application by ground and aerial equipment have culminated in the registration for practical use of the specific NPV's of the Douglas-fir tussock moth and gypsy moth.

NPV's of the European pine sawfly, tent caterpillars, fall webworm, and spruce budworm have similar potential for control of these major forest pests. Forest insect pathologists have been in the forefront of this recent research activity to identify, characterize, and utilize these agents in integrated pest management (Figure 9).

Nutrient Cycling and Its Relationship to Forest Management, Stream Quality, and Ecosystem Theory

Forest ecosystems play a key role in preserving landscapes and surface waters quality. Scientific study of nutrient cycling in forests has played a key role in elucidating these relationships. The linkages among vegetation, air, soil, and water, the pathways of movement of each nutrient element, and the processes controlling rates of transfer

A



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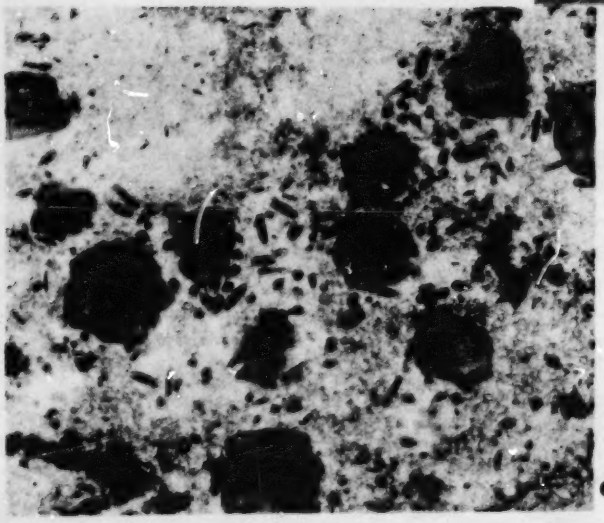

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Figure 9. Productive forests must be protected against injurious insects such as the gypsy moth. Basic research on diseases of these destructive insects will provide improved methods for insect control. These three pictures show: (A) appearance of a gypsy moth larva killed by nucleopolyhedrosis virus; (B) scanning electron micrograph of polyhedral inclusion bodies isolated from dead gypsy moth; and (C) ultrathin section through an inclusion body forming in the red blood cell of a gypsy moth larva.

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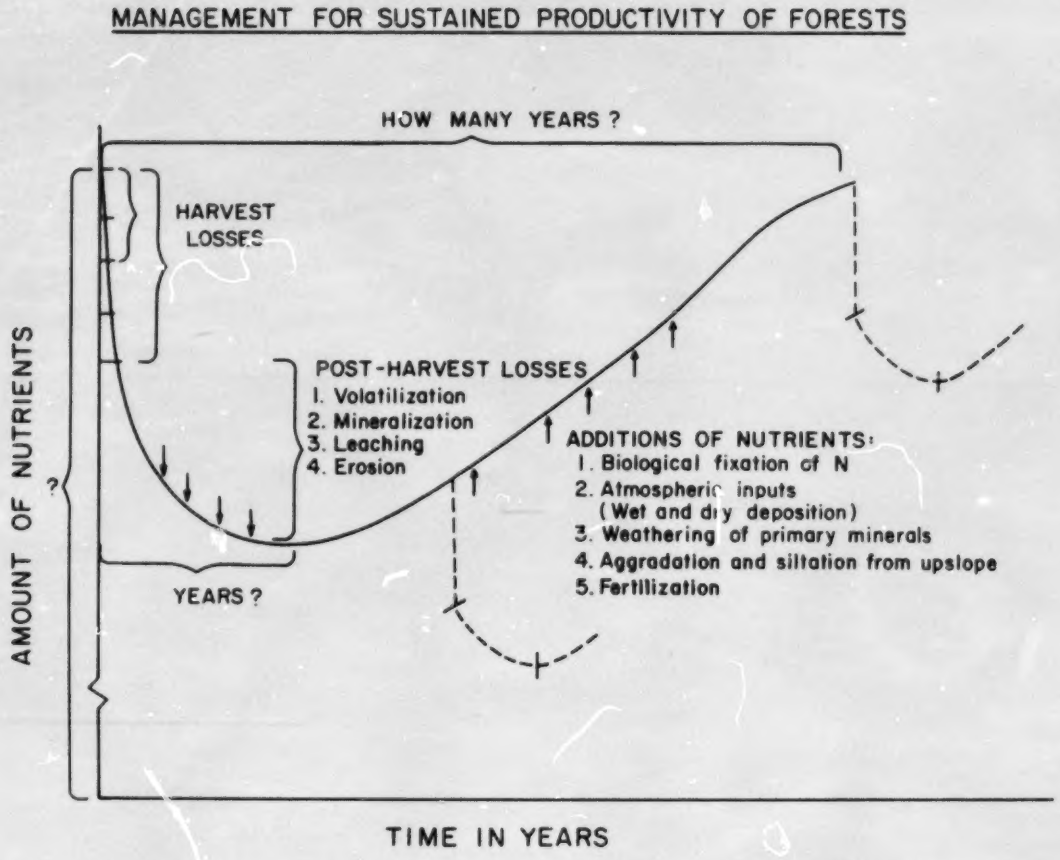


Figure 10. Management of forests for sustained yield requires an understanding of the nutrient dynamics of forest stands. Basic research is needed to determine the quantitative balance between *losses of nutrients* during and following harvesting and *additions of nutrients* by natural processes and management practices. Information is needed on the amounts of nutrients *lost* due to leaching, erosion, and volatilization in comparison with amounts of nutrients *added* by biological fixation, atmospheric deposition, weathering, aggradation from upslope, and fertilization practices.

have been systematically assembled and more clearly defined in forests than in many other types of ecosystems (Figure 10).

This systematic way of evaluating the nutrient dynamics of an ecosystem began with forestry research, where scientists sought to understand interrelationships between forests and other ecosystem components, including the atmosphere, soil, and drainage waters. Biogeochemical processes of the soil, physiological processes of the plants, and hydrological processes of the entire ecosystem are all necessary components to this understanding.

The concepts and theories derived from basic research in forest nutrient cycling have both practical and theoretical applications. Examples of such applications include:

(1) *Impact of forest management activities on the conservation and loss of nutrients:* Forest management activities, including harvesting, site preparation, and fertilization have the potential to trigger losses of nutrients through leaching. Mineral cycling studies have provided the basis for understanding such losses and the means by which they can be controlled.

(2) *Application of effluent waters and sludges from municipal and industrial sewage treatment on forest ecosystems:* Because of environmental and public health considerations, forest ecosystems are being used as sites for the disposal of unwanted sewage products. A fundamental understanding of the mineral

cycling rates and processes is necessary in order to develop ecologically sound bases for this use of forests.

(3) *Development of new insights into ecological theory:* Basic research on the transformation and transfer of nutrients among ecosystem components has led to new insights into ecological theory. Examples include: (1) ecosystem stability with succession, (2) the role of succession in nitrogen fixation, (3) importance of forest stand structure in nutrient stability, (4) importance of internal translocation of nutrients in maintaining the productivity of perennial ecosystems, and (5) importance of nutrient transfers among ecosystem components such as microbes to soil to plant (Figure 11).

(4) *Understanding the structure and function of stream:* Much current understanding of the function of stream ecosystems has been developed through nutrient cycling studies in integrated studies of terrestrial and aquatic ecosystems. These investigations have shown that most of the energy utilized within forested headwater streams is derived from the terrestrial environment, and that fundamental changes in energy sources will alter dramatically the biological and physical structure of the stream system.

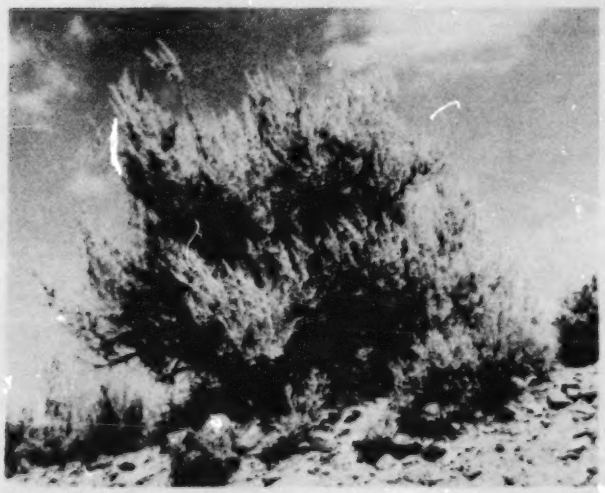


Figure 11. Wise management of range lands requires knowledge of the vegetation that thrives under arid conditions. Big sagebrush (*Artemisia tridentata*) is one of the most aggressive and persistent plants on more than 200 million acres of western range. Basic research is needed on genetic engineering of this plant. Recent findings show that improvements can be made particularly with regard to its protein content, digestibility, palatability, rate of growth, and resistance to drought, insects, and disease.

Fire Behavior Models

By 1965, the principles of meteorology in mountainous terrain and forests were fairly well understood. The principles of heat transfer in live and dead forest vegetation and the processes of flame spread through simple forest fuels were reasonably well established. There was, however, little quantitative understanding of the complex energy transformation processes typical in wildfire behavior. Rothermel, with Frandsen and Anderson, developed the first quantitative models of fire behavior in forests. For the first time, it was possible to predict the rates of fire spread, energy release, and fire growth given certain fuel, weather, and slope variables. These predictive models made possible the development of the following:

(1) a new and sophisticated National Fire Danger Rating System;

(2) prescriptions for prescribed burning;

(3) research and development on the application of infrared sensing principles and hardware to detect and monitor wildfires;

(4) a computer-oriented simulation system to compare alternative fire suppression plans and programs.

Fiber Saturation Point and its Significance to Wood Utilization

One of the most important fundamental concepts in wood utilization is the idea of a "fiber saturation point," defined as that moisture content of wood at which the cell walls are completely saturated, but there is no free water present in the wood cell cavities.

Basic research at the Forest Products Laboratory in Madison, Wisconsin, showed that the following properties of wood undergo major shifts at or about the fiber saturation point:

(1) Various mechanical properties—including strength, stiffness, and hardness—decrease sharply as moisture content

increases from ovendry conditions to the fiber saturation point, and then continue unchanged as additional free water is absorbed.

(2) Electrical properties are changed. Resistance increases enormously as wood dries below the fiber saturation point.

(3) As wood moisture content increases, swelling ceases at the fiber saturation point.

(4) Wood decay organisms generally do not function at moisture contents below the fiber saturation point.

These basic research discoveries significantly influenced the course of basic and applied research and the utilization of wood during the past 70 years.

Chipping Headrig

When logs are cut into lumber on a conventional circular saw or band saw, sawdust and slabs are produced as waste products. Through basic research on the energy requirements for various types of cutting devices, Koch conceived the idea of a chipping headrig that would produce square cants for resawing into lumber and pulp chips, rather than sawdust and slabs. This idea has greatly increased both the energy efficiency and the material-processing efficiency by which logs can be converted into useful products. This revolutionary idea was developed originally from inspection of very high speed photographs of the form and structure of wood chips produced by cutter heads altered to strike at angles varying from 0 to 90 degrees. These very basic research studies eventually led to an idea that has spread all over the world (Figure 12).

Figure 12. New processes for machining and chemical conversion of wood products increase the energy efficiency of production systems and aid in the development of new products from wood. Basic research on the design of new cutter heads provided the basis for developing of a shaping-lathe that will produce rectangular or octagonal as well as square, hexagonal, or round wood.

Selection of Materials for Construction of Laminated Beams With Specific Strength Properties

A series of experiments were begun in 1963 to (1) utilize the full range of grades of wood as they occur naturally in small and large logs, rather than the highly selected grades required for high performance beams; and (2) develop an economical assembly system to optimize the position within a beam at which each laminate should be placed. This research required the basic mathematical description of a wide range of strength properties for laminates containing varied numbers and positions of knots. Given these descriptions and the position within beams at which the properties of each laminate could be used to maximum advantage, it became possible to fabricate laminated beams of substantially greater predictability both in cost and strength. The concept is simple and has been applied by laminators all over the world (Figure 13).

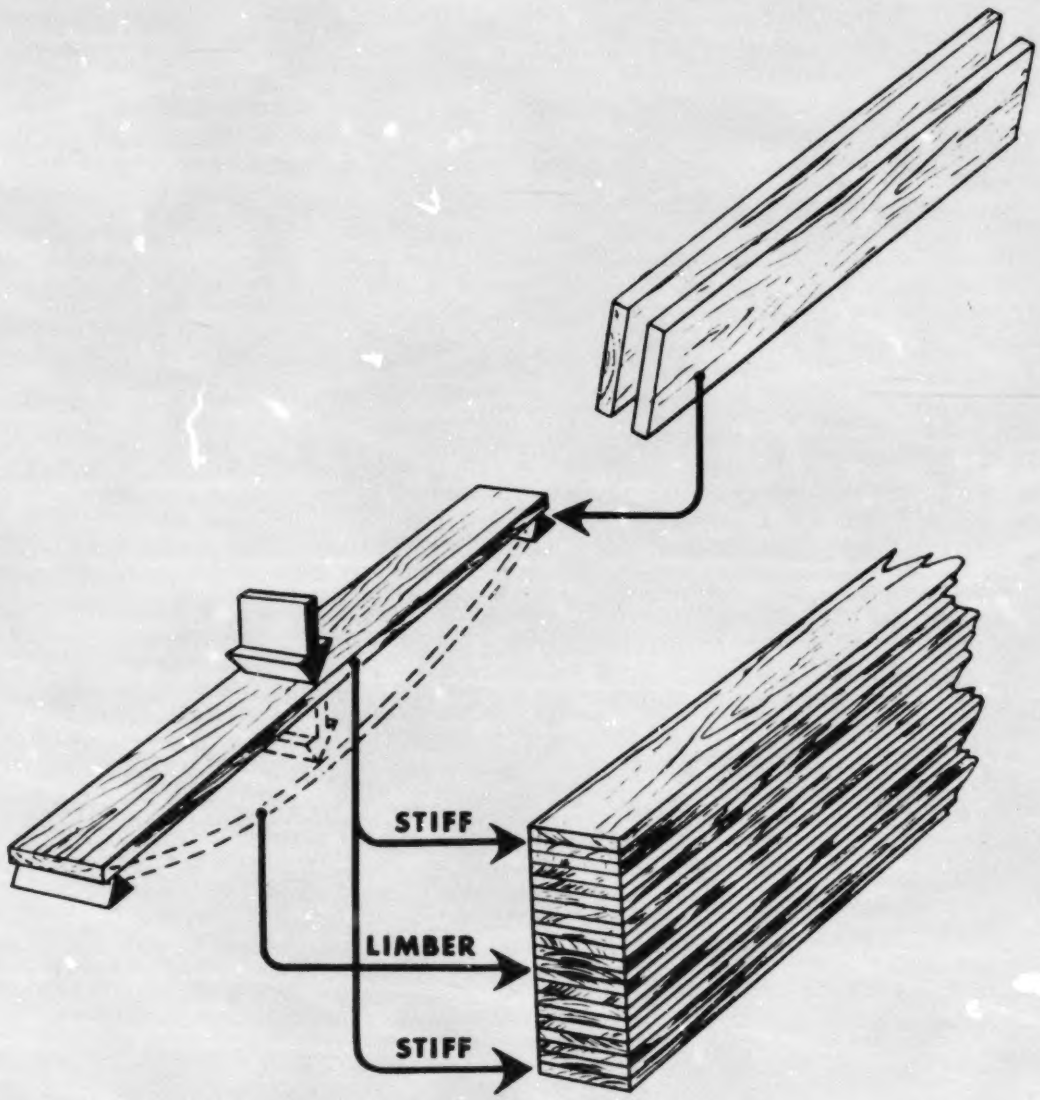


Figure 13. Laminated beams are one of the myriad of timber products produced from forest trees. Basic research on the relationship between the properties of individual laminae and the properties of the assembled beam have made possible the production of beams of substantially improved uniformity and strength.

VII. CHALLENGES IN BASIC RESEARCH FOR THE REMAINDER OF THE TWENTIETH CENTURY

"Basic research is a creative venture of high order. It flows from the minds of a relatively few men and flowers generally in a climate of quiet contemplation."

James Horsfall

During the Basic Research Conference, each National Task Force member was asked to identify areas of science and specific research topics which he believed offered the most challenging and valuable opportunities for basic research. After much discussion and debate, the participants recognized five general areas of inquiry within which various specific research topics could be classified. The five areas are:

A. Basic Biology
B. Ecological Research
C. Engineering and Materials Sciences
D. Economic and Consumer Benefits
E. Management Systems

The following discussion is intended neither to be exhaustive nor to set priorities, but, rather, to highlight some of the most promising opportunities for discovering important new concepts and principles.

A. Basic Biology

Forest and range land productivity is determined by the complex interplay of climatic, geochemical, and physical forces of the nonliving environment interacting with and influencing plants and animals occurring on these lands. Understanding the genetic and physiological aspects of forest growth is essential if we are to know the critical limits to forest and rangeland productivity.

Genetic limits to growth—Forest vegetation has remarkable genetic diversity. By virtue of their wide distribution and occurrence in natural, relatively undisturbed conditions, forest trees and wildlife offer unique opportunities to analyze the natural forces of competition and adaptation that have shaped the size, species, composition, and genetic structure of existing populations. Specific studies to expand our present meager understanding of genetic limits to growth should include the following:

- comparative analysis of the genetic diversity in populations of various forest trees and range plants and animals;
- in-depth studies of the genetics of forest and range pathogens and insects;
- determination of the heritability of traits that affect photosynthetic efficiency, rate of growth, and distribution of growth within individual trees;
- development of tissue-culture methods for mass propagation of forest and range plants;
- adaptation of genetic-engineering, protoplast-fusion, and recombinant-DNA methods to forest and range plants (Figure 14).

Physiological limits to growth—The availablity of nutrients from both atmospheric and soil sources is among the most important factors limiting growth on many forest sites. Basic research on forest nutrition and nutrient cycling is essential to better understand how forest trees and range plants exploit the nutrient resources available on various types of land and terrain. Specific studies should include the following:

- optimum nutrition experiments with various species and stands of forest and range plants;
- analysis of symbiotic and pathogenic relationships among higher plants, bacteria, fungi, and algae that contribute to nutrient availability on forest sites;

A

B

Figure 14. Enzymes govern the rate of chemical reactions in the growing of forest trees. Basic research on the enzyme proteins of pines is one of the first steps in genetic engineering of trees of superior form, rate of growth, and resistance to disease. These illustrations show (A) research technician separating pine embryo tissues and (B) electrophoresis apparatus used to separate enzyme proteins from embryo tissue.

- research on the developmental physiology and adaptability of plants and wildlife to their environment.

Competitional limits to growth—Intense competition among plants, animals and microorganisms characterizes all forest and range communities. Basic research is needed to better understand the mechanisms of these multicomponent competitive systems. The following specific topics deserve emphasis:

- mechanisms by which forest and range plants compete with each other, e.g., light, moisture, nutrition, etc.;

- direct and indirect effects of forest management on wildlife populations and behavior;

- concepts and principles of integrated pest management as adapted to forest and range ecosystems (Figure 15);

- seasonal and long-term changes in food resources as they influence the structure of fish, wildlife, and aquatic invertebrate communities;

- natural succession and planned disturbances within forest and streamside vegetation as they affect the total productivity of the stream and wildlife habitat.

B. Ecological Processes

Scientific management requires a detailed understanding of the dynamic changes in forest ecosystems as the forest regenerates, matures, and eventually declines in productivity. Such information is needed to establish guidelines for ecologically sound management under a wide range of forest conditions.

Nutrient, energy, and water transfer processes within forests—The various elements comprising the forest system are interrelated. For example, aquatic and terrestrial systems are tightly linked through transfer of energy, nutrients, and substances common to both. What one system may produce, the other may consume. Thus, forest

resource management requires a thorough understanding of the effects of management activities on forest plants, animals, and their environment. Priority needs for basic research include the following:

- determine how forest successional changes or disturbances affect the physical and biological structures within lake- and stream-side communities;
- define the processes, pathways and timing of water flow through forests and other wildland ecosystems.

Interactions with the earth's chemical climate—Sustained yield forestry is made possible by biogeochemical processes permitting exchanges of a great variety of substances among air, water, vegetation, and soils. Since the Industrial Revolution, industrialization, urbanization, and deforestation in tropical regions have greatly changed the quantities of beneficial nutrients and harmful substances in the air and surface waters. Understanding how these changes affect forest growth and productivity will require the following kinds of basic research:

- determine the effect of acid rain on the nutrient status and productivity of forest ecosystems;
- determine the influence of global changes in precipitation rates, carbon dioxide content, and temperature on forest and range ecosystems;
- determine the impact of tropical forest removal on global atmospheric changes and nutrient flux.

Ecological impacts of wildfires and controlled burning—Fire has always been an important feature of ecosystems in regions of seasonal rainfall. Current fire-control programs and other forest-management practices increase the hazard of destructive wildfire by aiding the accumulation of combustible biomass on the forest floor. Periodic prescribed burning can minimize these hazards, but it must be carefully managed. Wildfire and prescribed fire both damage and benefit soil, water, trees, wildlife and the atmosphere. Understanding and quantifying fire effects are fundamental to making decisions about fire control tactics and

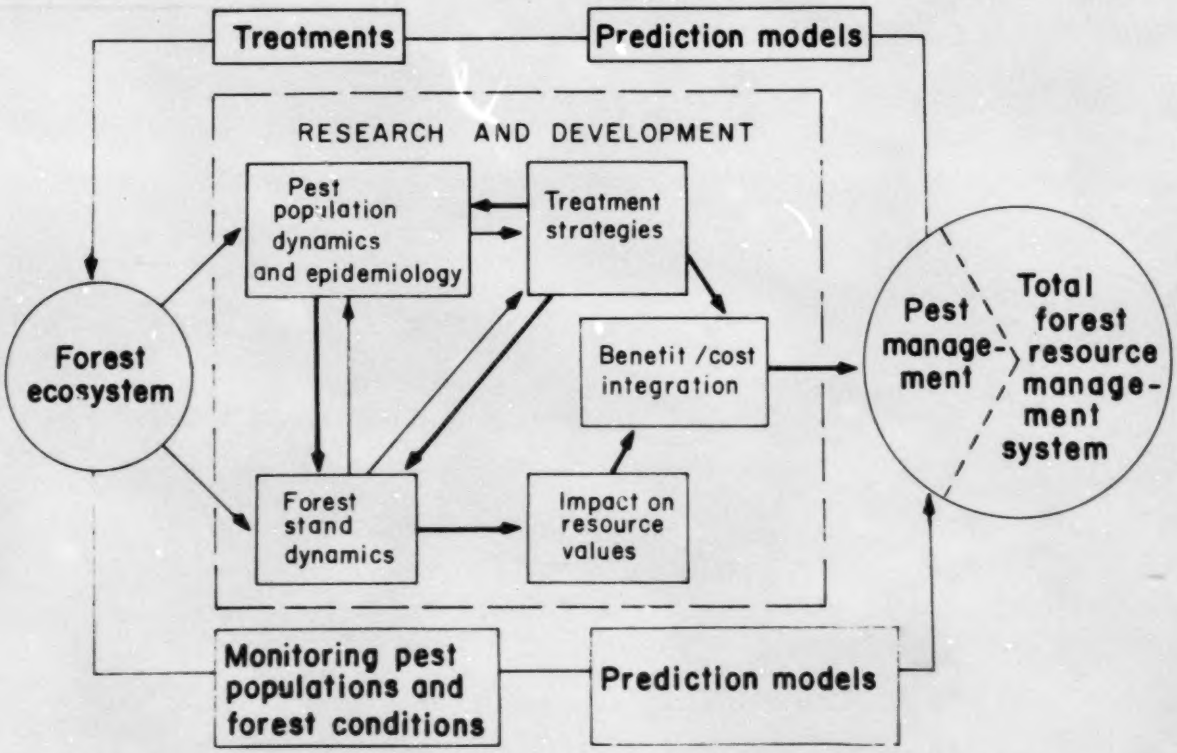


Figure 15. Integrated pest management is a concept of great practical value in forestry. Basic research is needed to determine the quantitative relationships depicted by the arrows and boxes in this conceptual model of a system for forest pest management.

prescribed burning. What is needed is a broader research foundation for innovative fire management. Such basic research should:

- develop new concepts by which to inventory the fuel hazard potential of living and dead forest biomass;
- analyze, describe, and quantify the effects of prescribed burning and naturally occurring fire on wildlife, forest vegetation, and water and air quality;
- analyze, identify, and describe the attitudes and behavior of people who deliberately or inadvertently start forest fires. This can be a basis for predicting man-induced wildfires and for designing education programs for fire prevention;
- integrate knowledge about forest fuels, meteorology, topographical variation, and fire processes into computer systems for predicting fire spread, intensity, growth rates, and control in mountainous forest areas.

C. Engineering and Material Sciences

Additional basic research is needed to attain maximum efficiency to develop new products and processes. All materials-based industries require an expanding knowledge of their raw material. This knowledge is still incomplete for wood.

Reconstituted wood products—In the future, reconstituted wood products will dominate a larger segment of the wood products market. This young technology has developed empirically— without a broad scientific base. The following basic research needs have been identified:

- determine how selection, breeding, and silvicultural practices can influence wood properties and composition;
- identify the mechanisms that control the internal bonding of wood and wood components;
- expand present knowledge of fluid movement in wood;
- develop processes that can economically utilize the complete biomass of small trees of mixed species;
- develop new concepts for protecting wood products against wood-destroying fungi, insects, and marine borers.

Forest engineering—Many forest operations require specialized equipment which must operate efficiently within the unique requirements of forest management. Equipment designers must clearly understand how such equipment affects the working environment and the soil. Priority areas for basic research include:

- identifying the direct effects of forest mechanical operations on soil mechanics and nutrient cycling;
- discovering harvesting concepts that will permit economical recovery of all sizes and species of forest biomass;
- developing new concepts for forest regeneration to alleviate undesirable effects of harvesting and other forest operations.

Wood for fuel and chemical conversion—Wood is a renewable source of energy and chemicals (Figure 16). But many basic research questions will have to be resolved if the best choices are to be made about when, where, and under what circumstances wood should be used for fuel and as a chemical feedstock. These questions can be resolved by basic research addressing:

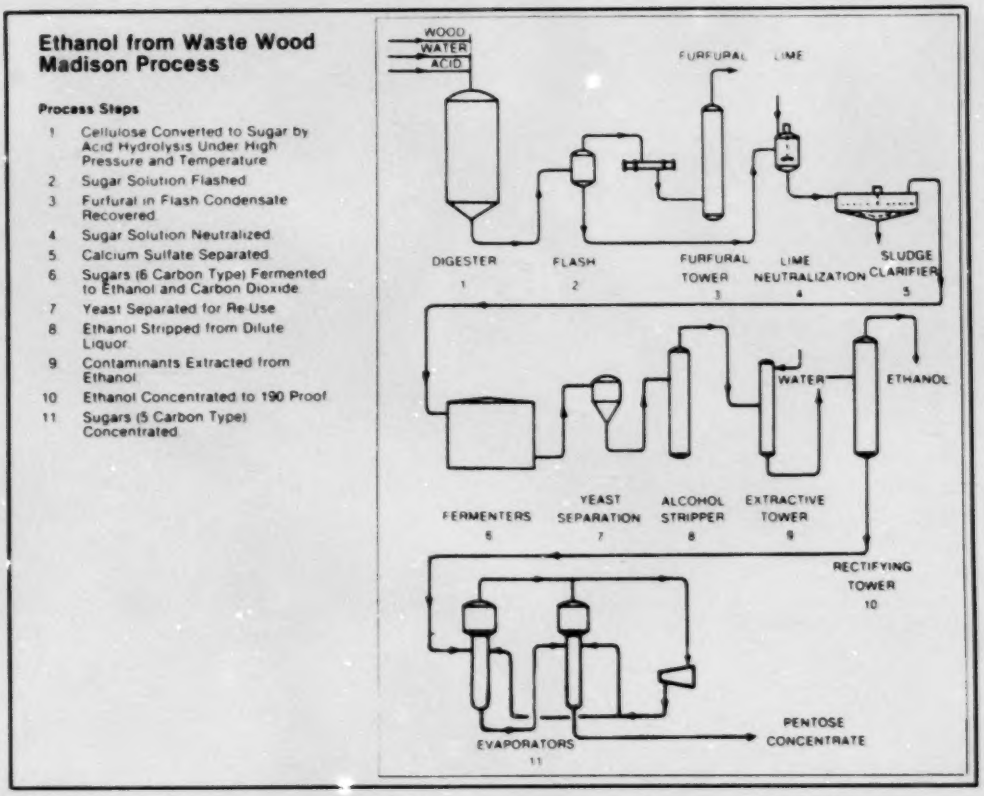
- the discovery of new principles for enzymatic, microbial, and chemical conversion of wood to chemicals;
- the development of a more adequate understanding of the chemistry of pyrolytic and combustion processes for lignocellulose.

D. Economic and Consumer Benefits

Research on consumer benefits draws on economics, sociology, psychology, and political science. Three broad categories of research associated with the forest sciences involve major consumer benefits. They are: (1) evaluation of consumer choices; (2) economics of natural resources; and (3) dynamics of natural resource policy and institutions.

Figure 16. Chemical and biochemical conversion processes can be used alone or together to convert wood chips to glucose, alcohol, ethylene glycol, and many other useful chemicals. Basic research on the kinetics of these reactions will greatly increase the economic efficiency of these processes. The process (A) production facility (B) shown in these pictures was used to produce ethanol from wood during World War II. As the costs of energy from nonrenewable sources such as oil and coal continue to increase, basic research on the production of energy and chemicals from wood will become more and more necessary to our national independence.

A



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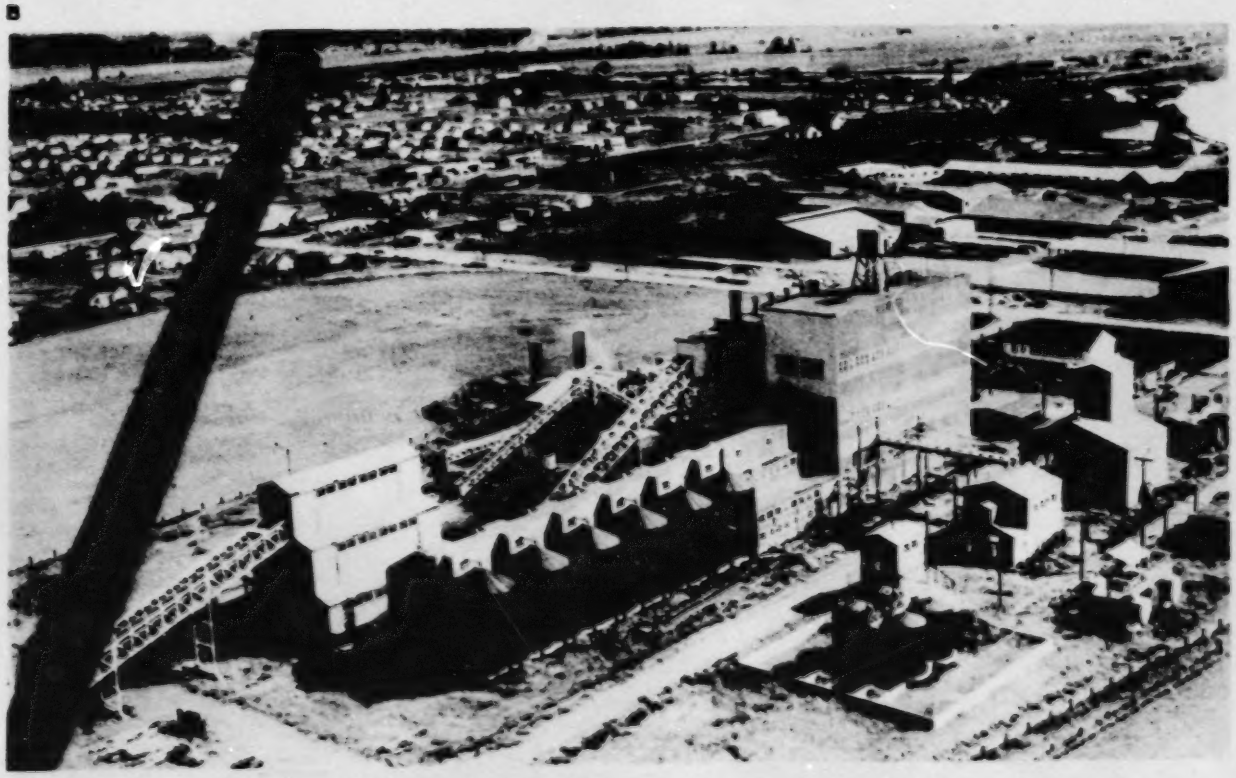

Consumer preferences—knowledge of consumer behavior and the tradeoffs inherent in consumption choices is basic to determining the values society attaches to natural resources and their products. Many benefits derived from natural resources are difficult to quantify in economic terms. To resolve some of the issues associated with consumer needs and desires, basic research should be directed toward:

- improving methods for measuring the social benefits of non-market goods and services from urban and rural forest environments;
- increasing understanding of the substitutability of recreational experiences for other experiences and needs in life;
- determining the impact of changing energy costs on the use of recreational facilities in urban and rural or remote areas.

Supply and demand relationships—Economic scarcity necessitates a wise allocation of natural resources. A fuller understanding of how basic economic concepts of supply, demand, and market exchange apply to production and consumption of goods and services from natural resources will enable decision makers to manage these resources more wisely. Basic research in natural resources economics must be directed toward:

- developing economic models which clearly assess the long-term effects on natural resources of changes in policies, markets, or managerial strategies;
- understanding and predicting conditions which limit the open market exchange process and necessitate remedial government action;
- determining to what degree markets for natural resource products and services reflect forces of supply and demand;
- analyzing and describing the dynamics of forest resource ownerships by size, distribution, managerial objectives, and other characteristics over time.

Policy and institutional consideration—As the world proceeds with intensive resource exploitation, a constant stream of policy and institutional questions emerges. Scientists must develop an understanding of the dynamic interactions among individual attitudes, socioeconomic forces, and institutional behavior. Such issues point to a need for basic research to work toward:

- describing the effects of exposure to rural and urban forests and related environments on attitudes, perceptions and behavior;
- developing conceptual ways to generate and analyze possible future conditions which may have significant implications for the present and future.

Damage potential of renewable resources—Changing demands for renewable resource outputs —timber, recreation, and the like—require hard, cost-effective decisions about allocations, financial and otherwise, for forest work activities. For

Figure 17. Some animals require cavities in older trees for safe hibernation or reproduction. If timber harvesting practices eliminate older trees, these animals may not survive in dens on the ground. Basic research on the reproductive behavior of various species of wildlife will help forest and wildlife managers develop timber-management guidelines that consider both timber production and wildlife values.

Figure 18. Cattle grazing on public forest and range land is a controversial issue because of potential conflicts with wildlife. Basic research on the concept and quantification of carrying capacity will help resolve these conflicts on the basis of sound scientific evidence. Recent findings suggest that late spring to early fall grazing of southern pine-hardwood forests may not decrease the food supplies for deer if the abundance of grass is used in determining the number of cattle per unit of land area. It appears that deer and cattle do not graze on the same plants in recently clearcut areas. Thus, moderate year-long grazing of these sites may have little or no effect on deer forage supplies.

example, wildfires, diseases, and insects damage and destroy renewable resources. The extent to which the resources are economically damaged depends upon the behavioral, biological, and physical characteristics of the damaging agent, as well as economic principles. We do not now know how to estimate the "damage potential" of renewable resources. We do not know how to determine optimum levels of fire protection or disease-control efforts. Therefore, basic research must:

- develop principles and methods for appraising the fire-, disease-, and insect-damage potential of forests and other renewable natural resources and for evaluating the economic efficiency of alternative programs to avoid these losses.

E. Managerial Sciences

Forests are used for many purposes, both consumptive and nonconsumptive: wood, range, water, wildlife and recreation. This multiple use leads to conflicts of interest and the need to consider many possible consequences of management decisions (Figure 17). The main goal of the managerial sciences is to develop analytical concepts and approaches which facilitate the efficient management of forest resources systems for specific or multiple uses (Figure 18).

Sampling and inventory designs—One of the most important requirements of management is detailed knowledge about the resources to be managed, especially in the case of complex natural ecosystems such as forests and range lands. Data bases and resource inventories must be current, accurate, and based on sampling rather than on a complete listing of all resources. High priority research in sampling and inventory is needed to:

- improve statistical sampling theory, concepts, and methods for continual multiple-resource inventory and monitoring;

- improve capacity to integrate data from ecological, social/behavioral, and production/utilization components of the total resource management system;

- improve concepts and methods for computer cartographic systems to simultaneously display multiple data sets, including spatial and temporal dimensions.

Optimization of management alternatives—Once the resources to be managed are adequately inventoried and described, models must be developed by which to predict change in these resources over time, including their response to alternative management regimes. To perfect such predictive systems, basic research is needed to:

- improve methods to predict the nature and extent of response of various natural resources to a full range of management activities, including minimum levels of management;

- improve tree and stand growth models that will allow continuing adjustments in predicting timber stand responses to changing technology, e.g., fertilization, waste water application, genetic tree improvement, integrated pest management, etc.

Validation of predictive models—Even when appropriate resource management models have been identified, the necessity remains for testing the validity of the system models and comparing alternative models of their behavior and accuracy. For this reason, greater emphasis needs to be placed on:

- developing concepts and procedures to test the validity of models that predict the responses of forest resource systems to management alternatives, and to calibrate these models for specific sets of conditions.

VIII. CLIMATE AND INSTITUTIONAL ARRANGEMENTS

"A really great scientific institution gets by with the least organization of the scientists that is possible."

James Horsfall

In considering the climate and institutional arrangements for basic research, the Task Force on Basic Research found it useful to consider the judgments of various scientists who have distinguished themselves in this form of scholarly work. Accordingly, we have listed below and included throughout the report a series of judgments from which we have attempted to distill a consensus view:

"The administration views basic research as a vital investment with a good return."

George Keyworth, II

"Any sensible policy towards science must recognize the essential role of basic research as the foundation of our economic program . . . ."

Murray L. Weidenbaum

"Freedom to inquire into the nature of things is a rewarding privilege granted to a few by a permissive society."

Sterling Hendricks

"Success in science requires three major attributes: (1) the experience, vision, and imagination to know what to do; (2) the education necessary to know or to learn how to do it; and (3) the energy and drive to get the job done."

Peter Koch

"The peer review process discriminates against interdisciplinary science and scientific thinking that is not au courant, even though it is creative and ripe with unusual potentialities for breakthroughs."

Thomas Jones

"A scientist must be somewhat of an iconoclast, a doubter, who constantly asks, 'Is it really so?' Scientists who accept things as they are rarely set up new hypotheses to test."

James Horsfall

"Scientists are intellectuals who view each other's work with quarrelsome interest."

Theodore Roosevelt

"Successful basic research is done by people who like to solve difficult intellectual puzzles."

Joseph Varner

"Basic research is to applied research as a tree is to the fruit that it bears."

Louis Pasteur

"The thrust of a committee is toward a standard of average performance . . . . Committees are consumers, even sterilizers of ideas, rarely creators of them."

Henry Kissinger

"The Mona Lisa was not painted by a committee."

A. Whitney Griswold

"As one member of a funding agency remarked to me, 'We admire innovation, but we don't trust it. And we fund what we trust.' "

T. M. Vogt

"Chance favors the prepared mind."

Louis Pasteur

"In the uncertain business of evaluating the performance of basic and useful research, the director looks at them separately, marvels at the scientists who produce both, appreciates those who produce either, and worries about those who produce neither."

Paul Waggoner

"Good research administration may be defined as removal of obstacles to research."

Peter Koch

"No institution can grow beyond its own image of itself."

John Murphey

Choosing the Right Scientists

Basic research is one of the most demanding of intellectual pursuits. Success requires a high order of curiosity, creativity in developing hypothesis and theory, skill in developing and executing imaginative research approaches, and disciplined rigor in interpreting evidence. Not every scientist is prepared by temperament, intellect or experience to pursue creative ideas. A healthy skepticism is essential to avoid the snares of conventional (comfortable) wisdom. Determination, persistence and self-confidence are essential shields against doubting and negative or inconclusive initial experiments. Objectivity is indispensable. So, too, is the ability to change tack when evidence overwhelms a hypothesis, to accept what Huxley called "the great tragedy of science . . . the slaying of a beautiful hypothesis by a series of ugly facts."

A scientist may be skilled in basic research at a particular stage in his or her career, but poorly prepared to sustain that effort. He may lose his touch, gain it late in his career, or may be either capable or inept over the whole of his scientific life. Thus, success in selecting, evaluating, encouraging, and rewarding basic research scientists is unusually challenging.

The successful basic research scientist must be willing to maintain an honest commitment over an extended period. An atmosphere of friendly or even spirited competition among research groups has often benefited basic (and applied) research. Although competition among laboratories always involves some risk of duplication of effort, experience shows that imaginative scientists usually gain a great deal from the efforts of others to duplicate their experiments. The accountant's abhorrence for "wasteful duplication" is widely and sometimes wildly exaggerated for several reasons: (1) actual duplication of scientific research is extraordinarily rare, particularly among imaginative scientists; (2) verification of results in different laboratories or field conditions greatly increases the strength of evidence supporting a given hypothesis or theory; and (3) such verification under different experimental conditions is essential to establishing the limitations of the theory and especially the acceptance of imaginative or audaciously new ideas in science.

The reward systems necessary to ensure optimum progress and achievements in basic research are quite different from those for applied research. Whereas the applied scientist may soon see the fruits of his or her discoveries in the field, this is much less likely to occur quickly in the case of the basic research scientist. Curiosity fulfilled, alternative hypotheses quietly laid to rest, the purely intellectual satisfaction of coming closer to the truth—these are very different rewards from those that accrue from watching the pilot plant under construction, launching a production-scale test, or inspecting the profit and loss statement of a corporation putting a research idea into profitable practice.

Seeing the definitive research paper in print, receiving an appreciative note from one's research leader, and earning the respect of fellow scientists are all very important to the basic researcher. The wise director of a center for basic research will know how to ensure that meaningful encouragement and rewards are provided for those who succeed in establishing a new principle or concept, or take an important step toward one or the other.

Effective reinforcement of self-confidence is at least as important to basic research scientists as it is to other aspects of intellectual endeavor. For many basic research scientists, the freedom and wherewithal to exercise their curiosities on prob-

lems they have chosen are just as important (sometimes more so) as a large salary increase.

Little objective information is available on the educational preparation of successful basic researchers. Studies have been made in certain fields, but not in all fields germane to forestry and renewable natural resources. The consensus within the Task Force on Basic Research is that the most successful basic research is conducted by scientists who have worked with other unusually imaginative scientists. The truth is that excellence often runs in scientific families and that imaginative scientists are chosen and taught by other imaginative scientists. This common thread in the sociology of science has special relevance to the concept of "centers of emphasis" discussed in the next section of this report.

Institutional Arrangements for Basic Research

Developing and maintaining a successful center for basic research requires extraordinary administrative skill. The guideposts for success are fewer and farther between than in applied research.

"Freedom to inquire into the nature of things" (as Sterling Hendricks put it so beautifully) is perhaps the most important single determinant of success. For this reason, the ideal leader of a center for basic research should be a person of vision, respected in his or her own right for achievements in basic research, and actively pursuing the objects of his or her own curiosity, as well as encouraging the curiosity of colleagues. The professional administrator has no place in the center for basic research, except in the business office intelligently "greasing the skids" for the researchers. The administrative staff must skillfully clear away every needless obstacle to progress so that the full creative energy of every scientist can be focused on research problems, rather than on circumventing some bureaucratic "snafu" in the purchasing department or the latest restriction on travel, bid requirements, or consulting policies.

In some cases, the research administrator knows very well what needs to be done to keep the research moving along productive lines. In most state and federal agencies, however, administrators seldom have the authority or budget flexibility to add new people, reshuffle assignments, or trade personnel to add new skills and upgrade quality. The research administrator needs as much, or more, freedom as his scientists. Setting up the basic research institution as a separate corporation with its own board of directors is one way to avoid oppressive bureaucracy.

Put more succinctly, the business of the business office should be solely to support the scientists on whose productivity the contribution and value of the institution must rise or fall.

Every effort must be expended to assemble the necessary laboratory and field research facilities, to provide adequate financial and subprofessional support, and to maintain a climate conducive to solving challenging intellectual puzzles. Contact with fresh young minds unencumbered with conventional wisdom and skeptical about the adequacy of established dogma and with older minds periodically refreshed by reassignment is always stimulating, so long as discussion is free and open and founded on logic and strength of evidence. This is the essence of scientific intercourse, a magnificently creative and self-perfecting system which must be nurtured in every basic research institution.

The most productive unit or organization in basic research is usually the small group—sometimes even a single scientist working alone, but more commonly a small team of two to five scientists working together on a common problem. Personnel must be chosen carefully and made to feel as team partners rather than rivals. The team should include essential disciplinary skills without being unwieldy in size. Over-specialization can impede collaboration. Occasionally, talent can be borrowed or a visiting scientist brought in to add additional skills for specific program purposes.

The scientific leader should be an experienced investigator. The group generally should be younger than the leader. The atmosphere should be quietly contemplative, the lab or office a comfortable place where a scientist can put his feet up on the desk and spend a day or a week in thought before embarking down the next experimental trail.

Financial Arrangements for Basic Research

Considerable debate centers on the most effective methods for funding basic and applied research. In some circles, the value of peer review

and competitive grants seems to be accepted as the only basis for rational governance. In other circles, formula funding is regarded as essential and peer review as a flawed system for ensuring conformity in scientific thought, rather than as a useful device for improving the quality of science.

We believe peer review should be recognized as a valuable tool with which to cut off the lower tail in the frequency distribution of quality in research. But it may very well cut off the upper tail of quality and imagination. Thus, in a mandatory system of peer review, every possible precaution must be taken protect imaginative ideas from the awesome power of negativism—even among well-meaning and conscientious scientists.

Formula funding is sometimes considered an anathema to progress, and competitive grants are regarded as the "only way" to ensure adequate quality and innovation in scientific research. This debate rages on, radiating much heat but shedding little light on the real difficulties of both systems. In our view, most of the failings of formula funding (weak scientists carrying on unending tests of unimaginative hypotheses) are consequences of inattentive or spineless administrators who want "peace at any price" and lack the courage necessary to purge the institution of scientists who are not advancing the frontiers. By the same token, many truly imaginative research ideas are rejected by some reviewers of competitive grants because the reviewers themselves lack the imagination to recognize an innovative proposal. Also, great waste is associated with repeated payment of start-up and termination costs when short-term funding does not adequately allow a realistic assessment of the hypotheses under investigation.

We believe a mixture of both types of support is desirable: formula funding to provide reasonable stability, especially for long-term experiments, must be coupled with the flexibility to pursue the very best instrumentation and facilities when imaginative ideas require a renewed investment. Greater firmness in administering formula funds and longer time frames for competitive grants would do much to increase the value of both systems.

Another current debate about institutional arrangements for forestry research has focused on the limitations of many scattered research centers and on the tradition of "one-man-shows" in weaker educational institutions. We endorse the concept of diverse "centers of emphasis" in basic research in universities and other research centers where the existing institution has already acquired a critical mass of capable scientists or where other inherent comparative advantages have been developed. Decisions about the location and continuation of such "centers of emphasis" must be based solely on the quality and quantity of new information to be gained from the research, not on institutional ambition, political equity, past traditions, whims of individual scientists, or short-term political expediency.

We also endorse the policy, established in many progressive research organizations, that a fraction of the professional time and facilities of every basic and applied research scientist should be available for pursuit of his own specific scholarly interests, whether related to his specific project responsibility or not. Experience in many institutions has shown that many scientists use this time to great scientific advantage. Many a scientist's most creative and valuable ideas have come out of this "unrestricted" time.

A special feature of basic research in the sciences undergirding forestry and renewable natural resources is the long time frame for development of forests and the long period of service expected of many timber products. Whereas a few growing seasons may suffice for genetic improvement of wheat, a few decades may be required to achieve important genetic improvement of forests. Forests persist from a few to many decades; the duration of our devotion to basic research must be adapted accordingly. Unfortunately, long-term funding is an anathema to legislative bodies with a 2- to 6-year longevity. For this reason, we recommend greater rigor in the administration of formula funding, with administrators held accountable for the scientific merit of their institutions and the long-term value of their output.

In the administration of competitive grants by public agencies and private foundations, we also recommend two alternative approaches: (1) use of 4 to 5-year intervals for awards rather than the typical 2 to 3-year interval currently in vogue at the National Science Foundation and the U.S. Department of Agriculture; and (2) use of the principle of "roll-forward-funding" so that recurring annual decisions for continuance are usually for a minimum of two additional years before termination.

EPILOGUE

It is a universal truth that basic research is vital to the continual health and growth of the scientific effort. So it is with forest science, a science composed of many very different but necessary disciplines. In this report, we explored how forestry differs from agriculture and why basic forestry research needs are not being met by current research efforts in our sister sciences. We identified some of the many unique contributions of the forestry sciences to the advancement of modern technology and to the general welfare of our society. But we also noted the serious gaps and deficiencies in the scientific foundation of modern forestry practice. All will agree that support for basic research would be nice, if we only had those extra funds. But basic research is not something merely "nice" or "extra." It is not a luxury; it is a necessity. Can we afford *not* to increase the share of science funding for basic research?

Today's fundamental research provides the foundation on which tomorrow's possibilities must be built. To quote Asimov:

> "The fact is that science and technology are one . . . there is only one scientific endeavor on earth—the pursuit of knowledge, and levels of purity are but man-made ways of obscuring that fundamental truth. The advance of knowledge rests on science and technology, neither can flourish without the other . . . ."

We must seek, in an ordered, rational manner, an understanding of these issues and translate this understanding into solid support for the basic research needs in forestry. If we do not, forest science will no longer be able to meet the needs of modern society. We believe that a well-balanced forestry science program can, in fact, be established once the issues are clearly defined. This, we feel, has now been accomplished.